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A Maturity Model for Rapid Diffusion of Innovation in High Value Manufacturing

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Abstract

In order to support accelerating the diffusion of innovations in high value manufacturing related to enabling flexible mass customization, this paper presents a research-based maturity model for forecasting the speed of innovation diffusion from ideation to market saturation. The model provides an early stage applied research view of (groups of) "game changing" variables, which accelerate diffusion of innovations to significantly reduce financial uncertainty and minimize the time to derive value from the original idea. The model is applied to multiple case studies related to the repurposing and customization of existing mass manufacturing infrastructures and processes to meet novel requirements. Case studies include among others a reference model based on a literature review, the diffusion of 3-D printing technology in manufacturing, the diffusion of novel cement manufacturing technology and the manufacturing of intensive care ventilators during the Covid-19 pandemic. The diffusion of innovation model applied is based on diffusion of innovation principles founded in the research of Everett Rodgers, the Bass Diffusion Curve and aligned to recent advances in living (eco-) systems theory. Special emphasis is placed on determining not only the relevance of "known-known" success factors for rapid innovation diffusion, but also on identifying "unknown-unknown" game changers enabling the required changes at pace. Key findings are that "game changing" factors for the innovations are primarily the interdependent availability of budget and resources to achieve market saturation, urgency of need shared by all participants, observability of impact (value creation) and compatibility with existing ways of work. Critical as well is population of all diffusion web roles with unique individuals. Further research is suggested regarding the dependency of assessed variable (groups) and the integration of Technical Readiness Level phases into the forecasting model.

Keywords: High Value Manufacturing, Diffusion of Innovation, Maturity Model, Living Systems, Innovation Acceleration, Game Changers

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1. Introduction

Innovation diffusion can be considered as new product introduction, which has a success rate of 45% +/- 35%, whereby the key factors for reducing the large uncertainty remain unclear [1,2,3]. Products are any offering, which creates a "known known" ability to act in context (knowledge) and that this knowledge fills the needs of an adopter [4]. The authors declare that all types of innovations in high value manufacturing can be treated as new product introductions and define the "success" of their introduction as their sustained use by late majority adopters / users [5]. While the success rate of new product introductions thus broadly equates to ~50/50, what is 100% certain is that every failure corresponds to a rate of user adoption, which did not result in the creation of sufficient value for the stakeholders of the new product venture within required time-frames. If innovations in high value manufacturing have a "50/50" change of being successful, then the relevant "lost" investments represent significant "lost" economic value that may be avoidable if their failure had been forecast robustly.

The diffusion of innovation curve from innovators to the late majority is used for exploring factors of the speed of new product introduction [1,5,6,7]. (Interdependent groups of) Factors influencing the speed of diffusion and thus significantly reducing financial uncertainty and minimizing the time to value creation are declared as "game changing" variables.

The growing capability of robust flexible mass customization in high value manufacturing is itself the result of such an innovation diffusion process [13,14,15] and selected case studies provide a cross-section of relevant perspectives.

Section 2 shares the results of a literature review. Section 3 presents the research method. Section 4 presents an exemplary case study. Section 5 discusses the results and key findings. Section 6 provides concluding thoughts and recommendations for future research.

2. Literature Review

The identification of "game changing" (groups of) variables enabling disruptively fast diffusion of innovations has to date struggled, especially because efforts fail to view the complete innovation journey from ideation to market saturation as an integrated and interdependent living (eco-) system of relationships between individuals assuming key roles (behaviours) [8,9,10,11]. The study is based on five logical axioms that, based on inductive reflection of the authors, define the direction of investigation and experimentation (a) the diffusion of innovation concept provides a robust framework for analysis, (b) the speed of innovation diffusion is the key variable in relation to financial uncertainty, (c) living (eco-) systems are a suitable basis for interpreting the speed of adoption through diffusion phases, (d) maturity models provide an easy to use communication path between diverse stakeholders for achieving consensus on current state, future state and the journey from one to the other, and (e) that a transition between adoption phases and aspired market saturation is set at a level of 84%.

The diffusion of innovation curve describes the journey of an innovation from ideation to market saturation [5,7,9,12]. It consists of user roles termed "innovators", "early adopters", "early majority", "late majority" and "laggards". The role of inventor is generally not considered.

Innovators are eager users, who enjoy experimentation and often collaborate with inventors. Innovators represent ~2% of the total market share. Early adopter users are typically (in-) formal opinion leaders that act as influencers sharing success stories of using the products. They are less interested in experimentation than innovators and are usually seeking improvements and efficiency. As with innovators, engagement requires little effort since they are open to change. Early adopters represent ~14% of the total market share. Early majority adopters are true followers open to change through innovation but require a sense of assurance through earlier adopter user peers. Early majority adopters represent ~34% of the total market share. Late majority adopters are in general not particularly interested in change and usually only adopt innovations, if there is a strong feeling that they must be part of mainstream changes. Late majority adopters represent ~34% of the total market share. Laggard adopters require significant evidence of change benefits while then adopting these extremely cautiously. Laggard adopters represent ~16% of the total market share.

The major financial and planning uncertainties associated with the diffusion of innovation from ideation to market saturation [13] give rise to concern in high value manufacturing spaces. The lower the speed of value creation, the greater the uncertainty associated with successfully evolving from the front-loaded high investment profile to a profit generation phase through asset usage. High uncertainty typically exists, because the needed changes are complex adaptions (innovations) of highly regulated design and manufacturing engineering solutions in very complicated whole product life cycles, which can span multiple decades. Additionally, these innovations often occur in deeply tiered globally diverse supply networks and (eco-) systems.

Disruptively accelerating the diffusion of innovation from ideation to market saturation requires acknowledgement of the complex adaptive nature of the innovation phenomenon and shifting the perspective from linear process to (living) (eco-) systems [11,14,15]. Innovation is understood as the ability to transfer knowledge from the point of origin to the point of highest need across the complete whole product life cycle and diffusion of innovation curve from ideation to market saturation [4]. Living (eco-) systems are that interplay of multiple stakeholders assuming multiple roles in a web of tangible and intangible exchanges that work towards a shared purpose [11,14,15]. The research paradigm applied is the idea as a "virus" diffusing through the living organism of innovation diffusion webs that in themselves represent a social phenomenon [16,17].

Maturity models such as the Capability Maturity Model Integration (CMMI) are widely used in industry to assess how capable an organization or system is in respect to continuous improvement [18,19]. This "wide use" is understood to correspond to the late majority stage of diffusion. Maturity models prove late adopters with a simple place to commence an assessment, which respects prior experiences and is based on common language and shared visions. The models provide easy entry into prioritization activities and a shared understanding of what this means within an organization or system, the definition of relevant performance indicators for learning and then control is then driven by culture and behavior thus permitting easier and faster adoption.

Based on the literature review the use of a six-level maturity model for summary of research results in a manner suitable for late adopters was deemed appropriate [13]. The level is determined from the scoring of the case study assessment tool and suggests the ability of the case study project to meet the projected schedule for deployment to the absolute market.

- Level 5: Launch / Delivery (Maturity: 80%-100%)
- Level 4: Request for Quotation (Maturity: 60%-79%)
- Level 3: Request for Proposal (Maturity: 40%-59%)
- Level 2: Request for Information (Maturity: 20%-39%)
- Level 1: Explore Strategy (Maturity: 1%-19%)
- Level 0: Do not use (Maturity: 0%)

The sum market share of innovators to late majority is 84% and declared as that market share leading to sustainable use of the innovation and corresponding creation of enough value to stakeholders for continuation of the venture. This principle is also applied to the individual adoption phases, where adopters from a next phase will only start adopting, if 84% of the adopters of the previous phase become users of the product.

3. Research Method

Based on the results of the literature review, a survey and analysis tool were created [20]. The research tool provides a high-level assessment of the underlying innovation diffusion web model shown in Figure 1.

This innovation web model, illustrated as a value network [21,22,23,24], provides a high-level view of how innovations are known to diffuse successfully based on the results of the literature review. Key elements are (a) "roles" signifying the behaviors of (b) individual participants, who (c) transact directional tangible deliverables and (d) intangible directional deliverables.

The narrative starts with the inventor(s) receiving an intangible challenge from Key Users. Receiving may hereby be the result of a purposeful interaction or simply the awareness of a challenge faced by Key Users. Inventor(s) explore the challenge in collaboration with the Super User(s) and develop an idea with context explanation and tangible prototype, which is shared with the Product Owner(s). The Product Owner(s) transform the input from Inventor(s) into a potential tangible solution for the users accompanied by an intangible explanation of why and how this solution can generate value. The solution and the value proposition are transacted with the Business Sponsor(s). The Business Sponsor(s) shape the solution and value proposition into a tangible opportunity and transact it with the Influencer(s). The Influencer(s) market the solution and value proposition to the Key User(s) in order to generate an intangible expression of interest, which the

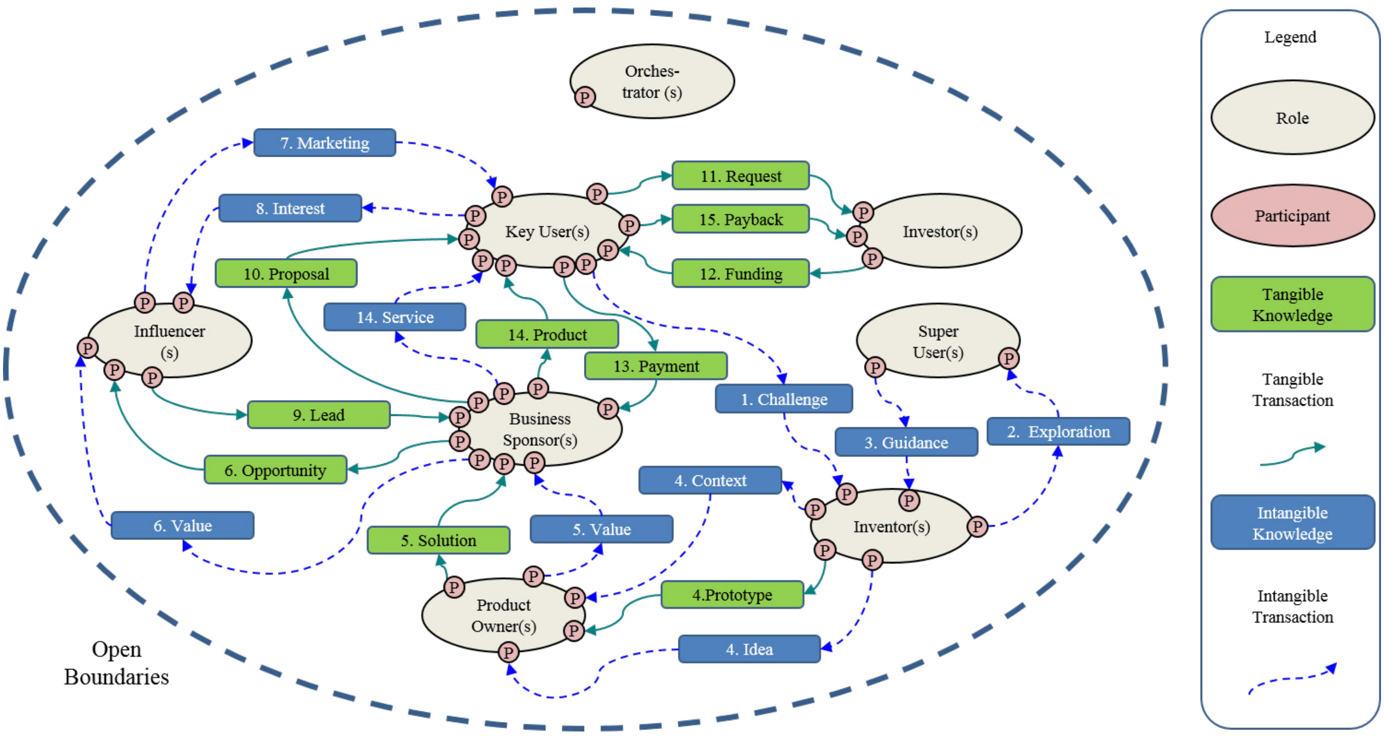

Figure 1. Generic Diffusion of Innovation Web [21]

Influencer(s) convert into a tangible lead that is passed to the Business Sponsor(s). The Business Sponsor(s) broker a tangible commercial proposal for purchasing the solution to the Key User(s). Upon receiving the proposal, the Key User(s) request funding from the Investor(s, who (in the perfect case) respond by providing the needed funding to the Key User(s), which is then used as payment for the solution to the Business Sponsor(s). Upon receiving payment, the Business Sponsor(s) facilitate the tangible product for the solution and the relevant intangible services to the Key User(s). Key User(s) then apply the product and service to resolving the challenge initially issued to the Inventor(s) and then provide payback to the Investor(s) in return for the funding provided.

Diffusion readiness of the innovation was assessed for the idea and for the (population of the) innovation system through which it needs to traverse. The assessments for all attributes were performed qualitatively by the interviewees on a Likert scale of 0 (Not at all) to 5 (Very High).

Based on Rogers [5] the innovation attributes examined are: degree of innovativeness, technical readiness level, budget and resources, number of competitors, degree of complexity, compatibility with existing ways of work, ease of understanding, ease of use, ease of adaptation, ease of trialing, observability of impact, urgency of need, and degree of certification. The score for innovation maturity is the averages for all answers to the questions "Is your idea ready to diffuse rapidly to late adopters?" and "How confident are you in your above assessment of the idea?". Averages are multiplied and divided by the maximum possible score in percent (%).

Based on Allee and Schwabe [22] the population attributes examined are their behavior in the innovation diffusion web in respect to urgency, priority, motivation, domain competency, collaboration preferences and degree of voluntary engagement. The innovation web must be populated by at least one unique individual for each of the core and accelerator roles. Core roles (key user, inventor, product owner and business sponsor) are needed to bring the innovation to life. Accelerating roles (investor, influencer, super user and moderator) give the diffusion of the innovation that acceleration needed in order to arrive at 84% market saturation within the planned timeframe.

The score for the roles and individual participants is averaged for all answers to the roles and participants questions multiplied and divided by the maximum possible answers to arrive at a relative score in percent (%).

The overall maturity level is determined by multiplying the score for "Idea for Diffusion" and "Roles and Participants". Weighting by multiplication was chosen as the relevant arithmetic method based on the underlying living systems principle of the maximum number of directional relationships between individuals assuming roles in the innovation web, which represent an exponential curve. For each factor assessed the interviewee was also asked to assess their degree of confidence in their answers. The assessment template then used the generic diffusion of innovation algorithms to forecast the diffusion of the innovation through the innovation systems, whereby an assumption was made that each phase started only when 84% of the target adopter category had been reached.

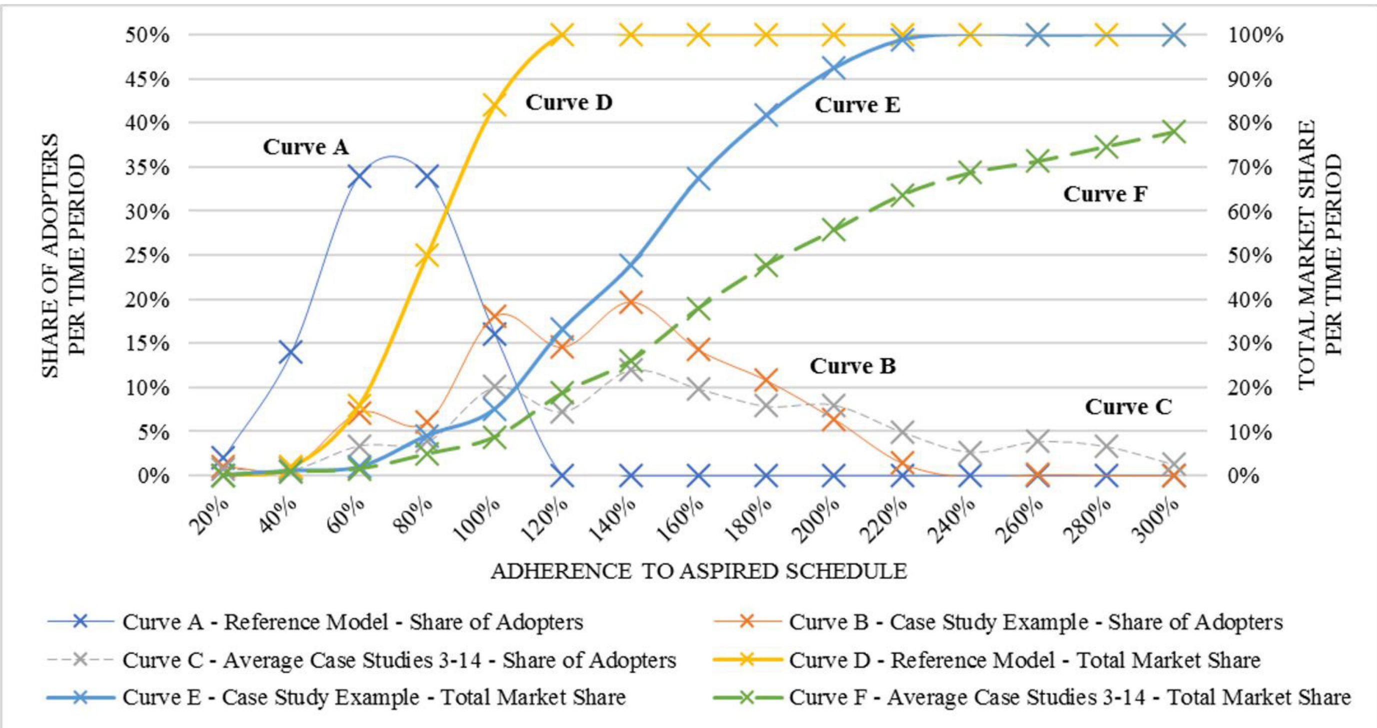

Figure 2. Diffusion Forecast for Exemplary and Wider Case Studies

4. Case Studies

A series of case studies were completed. As described in Table 1, case study 1 reflected the reference model derived from Rogers [5]. The exemplary case study 2 is based on the review of a survey analysis case study concerning the adoption of 3D-printing technologies in manufacturing in the US [25]. Case studies 3-14 were derived from personal interviews with organizations and reviews of selected cases in literature.

The number of new adopters over time ($s_a(t)$) was calculated using the Bass Diffusion Model [26] based on the Overall Co-Efficient of Innovation (p), the Overall Co-Efficient of Imitation (q), Total Market Size (m) and the Cumulative Number of Adopters (S(t)).

$$s_a(t) = p + (\frac{q}{m}) * S(t) * m - S(t) \tag{1}$$

$$p = m * s_r(t)) \tag{2}$$

$$q = p * s_r(t)) \tag{3}$$

m was set constant at 100 and S(t) as a percentage of m.

The calibration factor for p was determined by taking the calibration factor for q and multiplying that by the product of the average score and confidence of idea attributes assessment.

The calibration factor for q was determined by taking the average percentage (%) maximum score for all population questions multiplied by the average percentage (%) maximum confidence score for all confidence questions.

Figure 2 illustrates the results of the forecast model for the exemplary case study. The results of the forecast model were validated for robustness against the case study information.

Curve A shows Case Study 1 Reference Model share of adopters per time period. Curve B shows this for the exemplary case study 2. Curve C shows the average share of adopters per time period for case studies 3-14. Curve D shows Case Study 1 Reference Model total market share over time. Curve E shows this for the exemplary case study 2. Curve 4 shows the total market share over time for case studies 3-14. For the wider set of case studies, the assessment results were translated into a maturity level structure aligned to industry standards as discussed in the literature review.

Validation interviews concluded that the forecast diffusion patterns represent a robust view of the project history. Variables needing attention for shifting the actual projection to the ideal projection required clarification of and commitment to financial funding and resourcing. This case study equated to a maturity level of "2" which means that it is suitable for requests for information to support the design of a more robust plan only. Improvement actions derive directly from improving scoring to the assessment question [27].

5. Discussion of Results and Key Finding

The key findings are based on the results of the wider case study analysis and focus on innovation maturity, population maturity, overall maturity, the degree of schedule adherence forecast and confidence in the forecast as shown in Table 1. Key insights from covariate analysis of results were:

- The lower the total diffusion time, the higher the overall maturity score of the accelerator roles and the higher the overall maturity score for the idea in respect to availability of budget and resources, urgency of need, observability of impact and compatibility with existing ways of work.
- Technical readiness level and degree of complexity do not correlate significantly with the total diffusion time.
- Individual maturity level of roles correlated less to total diffusion time than to the maturity of accelerator roles.
- The more accurate the forecast of total diffusion time, the

Table 1 Wider Case Study Results

Case	Context (Detailed assessment results available in the assessment tool [27])	Idea Maturity	Popu-lation Maturity	Overall Maturity	Schedule Forecast	Assess-ment Con-fidence
1	Reference Model: Perfect innovation diffusion curve [5].	5 (100%)	5 (100%)	5 (100%)	100%	100%
2	Case Study Example: Adoption factors for 3D-printing technologies in US manufacturing [25]	3 (44%)	4 (74%)	3 (50%)	180%	78%
3	MES Deployment: Introduction of an MES system at an aerospace OEM from 2015-2018 [A. Hoessler, personal communication, May 16th, 2020].	3 (44%)	4 (73%)	2 (22%)	> 300%	69%
4	ICU Ventilator: An open manufacturing collaboration in 2020 for electric ventilator units for ICUs [D. Gaspar, personal communication, May 30th, 2020].	3 (44%)	4 (72%)	2 (32%)	260%	60%
5	Modular Bridges: A 2019 sales effort for innovative modular bridges for civil infrastructure [A. André, personal communication, Nov. 12th, 2019].	4 (64%)	4 (74%)	3 (47%)	180%	60%
6	Concrete Recycling: A 2019 patented proof of concept for returning cement to its original components [A. Bogas, personal communication, May 20th, 2020].	3 (50%)	2 (27%)	1 (14%)	> 300%	23%
7	Thin Metal Milling: A 2018 patented pilot for high stability milling of very thin metal components [T. Tunc, personal communication, May 28th, 2020].	3 (59%)	4 (72%)	3 (42%)	180%	69%
8	Cannabis Medication: 2018 manufacturing recipes for cannabis-based medications [S. Santos, personal communication, Oct. 16th, 2019].	4 (62%)	4 (68%)	3 (42%)	260%	69%
9	Bio Electric Hybrid Aircraft: 2020 concept study for heavy payload, short space take-off and landing [N. Price, personal communication, May 29th, 2020].	3 (48%)	3 (48%)	2 (22%)	> 300%	58%
10	Augmented Reality: 2020 PhD focused on “Augmented Reality for Maintenance” [J. A. Erkoyuncu, personal communication, May 26th, 2020].	4 (72%)	5 (86%)	4 (62%)	> 300%	86%
11	Safer Product World: A 2020 service for the design of intelligent, effective and safer products [B. Hardy, personal communication, May 25th, 2020].	3 (53%)	4 (75%)	3 (40%)	260%	73%
12	Adjustable Shin Guards: A 2016 product for adjustable, high safety performance sports shin guards [D. Gaspar, personal communication, May 30th, 2020].	4 (76%)	4 (69%)	3 (52%)	180%	79%
13	SHAKE-IT: A 2020 new product launch for a series of five fresh-frozen smoothies [L. Sharir, personal communication, June 5th, 2020].	5 (84%)	4 (73%)	4 (61%)	180%	83%
14	Precalciner: Post 1970 diffusion of precalciner technology in the U.S. cement industry [28].	5 (85%)	4 (79%)	4 (67%)	180%	90%

higher the confidence of interviewees in answers.
- The lower the TRL of an idea, the more significant it becomes to ensure budget and resources.

The verification of insights with the 11 interviewees (see Table 1) resulted in those interviewees with primarily industrial experience supporting the tenor that it is common to launch projects without appropriate funding, resources or sponsorship and hope for the best, while those interviewees with primarily research experience agreed on the necessity of integrating Technical Readiness Level (TRL) [29] and market diffusion perspectives and that diffusion patterns would be applicable to the TRL process as well. A wider applicability of the research method however requires its application to a larger set of examples.

6. Conclusion

Insights gained suggest "game changing" factors for innovation are primarily (a) the availability of budget and resources to fund the effort to achieve market saturation, (b) a high level of urgency for the need shared by all participants to ensure a maximum level of attention among conflicting priorities, (c) observability of impact for all participants to validate value creation, (d) compatibility with existing ways of work of all organizations to minimize potential process changes, and (e) population of all roles with unique individuals.

From an overarching perspective, the researchers conclude that the idea to market saturation paradigm creates a novel and effective path for improved understanding acceleration of innovation diffusion [30,31]. This is particularly relevant for efforts to increase capabilities for flexible mass customization as highlighted in the introduction since such by default represent not only technological, but also social phenomena that can best be understood from the perspective of the declared axioms and path of investigation Further research is suggested into the dependency of assessed variable (groups).

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